ICE DETECTOR CONFIGURATION FOR IMPROVED ICE DETECTION AT NEAR FREEZING CONDITIONS

BACKGROUND OF THE INVENTION

The present invention relates to a configuration of an ice detector that detects ice at temperatures that are near freezing and which has a pressure field that reduces the pressure on surface regions so that such regions cool to a lower temperature as air flows past the detector to detect ice prior to formation on critical aircraft surfaces. The ice detector is used on air vehicles and provides a warning of actual ice accretion.

Existing magnetostrictive ice detectors perform well over the typical aircraft performance envelope. However. as more and more aircraft are designed with high performance wings situations may arise at temperatures near freezing where ice will form on a wing while the conventional ice detector provides no information indicating ice. The critical temperature is defined as the temperature above which no ice will form on a structure given the aircraft configuration and other atmospheric conditions. The critical temperature can be different for a typical airfoil configuration and for a conventional ice detector, at the same airspeed. The conventional ice detectors generally have a circular cross section probe.

A paper entitled "Equilibrium Temperature of an Unheated Icing Surface as a Function of Air Speed", Messinger, B. L., J. Aeronaut. Sci., p. 29–42, January 1953, provides insight into the thermodynamic balance at temperatures near the critical temperature for two dimensional cylinders. There comes a point in which the aerodynamic heating associated with direct impact cannot overcome the propensity of supercooled droplets (liquid water at temperatures below freezing) to change phase and remain on the structure as accreted ice. If the temperature is cold enough this will occur. In practice, the size of the ice detectors relative to the size of most wings can be selected so as to cause ice to accumulate on the detector faster than accretion on the wing, which is the intended result. This, however, did not take into account the fact that airflow over the lifting surface of the wing or airfoil can create localized areas of temperature colder than the ice detector. Hence ice accretion may occur on the wing at temperatures warmer than the conventional ice detector.

At high angles of attack, such as those present in takeoff and landing of an aircraft, the airflow around the leading edge of the wing accelerates around the top and creates a region of lower pressure or vacuum relative to ambient static pressure. This lower pressure in turn creates a temperature drop near the leading edge of the wing, and in the most extreme cases the area where the lower pressure occurs experiences ice accumulation. In other words, if supercooled droplets of water are present in the area of the wing where there is a lower pressure and a sufficient temperature drop occurs, ice will form.

SUMMARY OF THE INVENTION

The present invention relates to an ice detector strut and probe assembly that has a geometrical configuration that will alter the pressure distribution around the probe and reduce the temperature at some regions of the probe to a level less than the temperature on the critical surface of the aircraft that is to be protected from ice formation.

The geometrical configuration of the probe assembly can be an airfoil cross sectional shape, or can be a cylinder with a strut that alters the airflow to achieve the desired pressure distribution.

In one form an airfoil cross section probe is oriented relative to a wing so that as the angle of attack of the wing increases, the angle of attack of the airfoil-shaped ice detector probe also changes and provides regions where a lower pressure occurs than at the associated wing surface. Using a probe with a shorter chord length, and having an appropriate airfoil shape relative to the shape of the wing, results in accretion of ice on the probe at temperatures above the critical temperature of the wing. Thus, ice accretes on the probe at temperatures warmer than that of the wing.

The airfoil-shaped probe is positioned so that the pressure field on the probe and adjacent to the probe is similar to, but creating lower pressure than, the wing airfoil at high operating angles of attack.

Additional forms of the invention show a cylindrical tube probe, that projects normal (or perpendicular) to the aircraft surface, and is arranged with a strut which modifies the flow past the probe in order to reduce the temperature on the probe. In other words, the strut geometry decreases the pressure and temperature at the probe surfaces to a level below that created by the wing or other structure with which the ice detector is used. In particular, the strut can incorporate bodies either fore or aft of the cylindrical probe with which to alter the pressure distribution around the probe.

Another form includes an axially extending rib on a lateral side of the probe. The rib will cause flow separation around the probe resulting in uneven or asymmetric pressure distribution with areas of the probe at a lower pressure than the aircraft skin and thus at a lower temperature.

Other methods can include strut and probe assemblies that have longitudinal axes that are not normal to the surface on which they are mounted, but inclined either forwardly or rearwardly so that the airflow past the probe is modified due to the probe inclination relative to the direction of airflow.

The flow can be guided and in all instances, the ice detector strut and probe assembly is formed to provide a pressure at a surface portion of the ice detector probe that is less than the pressure on the critical surface that is being protected by the ice detector. The reduction in pressure also causes a reduction in the temperature at the ice detector surface, thereby causing ice accretion at a warmer temperature than with conventional probes. The local pressure distribution on the ice detector probe is modified by the strut geometry, sweep of the probe, or by the formation of the airfoil shape cross section of the probe.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a fragmentary schematic front view of an aircraft having an ice detector made according to the present invention installed thereon;

FIG. **2** is a schematic sectional view taken as on line **2**—**2** in FIG. **1**;

FIG. **3** is a graphical representation of a typical airfoil indicating ice formation conditions and plotted as critical temperature versus angle of attack;

FIG. **4** is a schematic representation of the airfoil-shaped ice detector probe of the present invention showing its size in comparison to a typical ¼" diameter cylindrical probe;

FIG. **5** is an enlarged representation of the airfoil-shaped ice detector of the present invention illustrating ice accumulation as predicted by a computer simulation;

FIG. **6** is a top view of a typical ice detector made according to the modified version of the present invention;

FIG. **7** is a rear view of FIG. **6**;

FIG. **8** is an end view of the ice detector of FIG. **6**;

FIG. 9 is a top view of a further modified form of the present invention showing an ice detector having an afterbody;

FIG. 10 is a rear view of the ice detector of FIG. 9;

FIG. 11 is an end view of the ice detector of FIG. 9;

FIG. 12 is a top view of a modified form of the invention including a forebody on a leading side of an ice detector probe;

FIG. 13 is a rear view of the probe of FIG. 12;

FIG. 14 is an end view of the probe of FIG. 12;

FIG. 15 is a top view of a further modified form of an ice detector probe of the present invention;

FIG. 16 is a rear view of the form of the invention shown in FIG. 15;

FIG. 17 is an end view of the ice detector probe of FIG. 15;

FIG. 18 is a top view of an ice detector showing a rearward sweep or inclination to an ice detector probe; and

FIG. 19 is a top view of an ice detector probe having a forward sweep or inclination.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

In FIG. 1, a typical aircraft indicated at **10** is of conventional design, and includes an airfoil cross section shape wing 12, and as shown has an ice detector probe assembly **14** made according to the present invention, supported on the skin or outer wall **16** of the aircraft. The ice detector probe assembly **14** is positioned relative to the wing **12** at a known location that is selected to provide for detection of ice as air flows past the wing and the aircraft skin **16**. In FIG. 2, it can be seen that the ice detector probe assembly **14**, including rounded upstream section **13** and the downstream section **15** forms an airfoil cross sectional shape.

In performing analysis of the effectiveness of an airfoil cross section ice detector probe, LEWICEv 1.6 (or a comparable program), a Computational Fluid Dynamics (CFD) simulation of icing environments, can be used to parametrically determine the effect of variables such as liquid water content (LWC), Median Volume Diameter (MVD), ambient temperature, altitude, airspeed and probe and airfoil (wing) geometry through a series of analyses. The results of these analyses provide direction for certification authorities, including the U.S. Federal Aviation Administration, the Joint Airworthiness Authorities, and Transport Canada, who must certify aircraft as being airworthy. The analysis performed was to use a test structure comprising a typical airfoil cross section for a wing, and analyze it at a single angle of attack. For that angle of attack, the ambient temperature was dropped at a given or reference airspeed to determine if ice was forming on the test airfoil. Once ice began to form, the temperature at which the formation took place was deemed the "critical" temperature for that geometry, airspeed, angle of attack, altitude and LWC.

FIG. **3** illustrates the results of a series of tests, plotting the critical temperature (the temperature below which ice accretes on the test wing airfoil) in degrees Centigrade (or Celsius) versus angle of attack (AOA) utilizing a Whitcomb airfoil wing, that was one meter long, and was used with airflows of 150 Knots true airspeed (KTAS). The Whitcomb airfoil is an example of a super critical airfoil used in high performance aircraft.

The plots include a plot **20** indicating ice will form below a particular temperature on this airfoil, and plotted along with it is a plot **22** of the average critical temperature. Plot **21** indicates temperatures above which ice will not form.

The bottom curve is the most negative localized pressure coefficient, indicating that the more negative the pressure

coefficient, the more potential there is for cooling and thus for ice formation. The aerodynamic pressure coefficient C_p is defined by:

$$C_p = \frac{P_l - P_a}{q_c}$$

where P_1 is local static pressure, P_a is ambient static pressure, and q_c is the impact pressure. The pressure coefficient (C_p)is shown on the right-hand side of the figure. The horizontal line **26** represents the critical temperature of a typical ice detector that has a circular cross section. A circular cross section is not affected by angle of attack, and thus the line **26** is horizontal and is slightly above −1.0° C.

In a review of FIG. 3, it can be seen that above about 5° angle of attack, the critical temperature for the Whitcomb airfoil ice detector probe is predicted to be higher than the critical temperature of a typical cylindrical ice detector represented by line **26**, and this means that ice will form on the airfoil before it forms on the ice detector. For example, at 6° angle of attack, ice will form on the airfoil with the ambient static temperature below −0.65° C. For static local temperatures above this, no ice will form. Above about −1.0° C., the typical cylindrical probe ice detector will not detect ice. If the airfoil is moving at a condition of 6.0° angle of attack, there is an opportunity for ice to accumulate on the wing and not on the ice detector.

The flow conditions have to be balanced or put into perspective by the flight envelope of the aircraft. It is unlikely that a commercial aircraft will fly at both high angles of attack and high speed. The situation that is shown in the plot of FIG. **3** is one that is met by aircraft flying under high performance conditions. It is believed that an important feature of the flowfield is the minimum pressure, which is the location where the temperature is the lowest. In FIG. 3, the minimum pressure curve **24** is indicated in the form of local pressure coefficient. The more negative that parameter, the more potential there is for cooling and consequently ice formation. In the case of an ice detector of conventional cross section design (a circular cylinder), the minimum pressure is given at a pressure coefficient of −3, assuming an ideal potential flow. The minimum pressure coefficient on the Whitcomb airfoil on the other hand, surpasses −3 after about 4.0° angle of attack. Thus at angles of attack greater than 5.0°, the typical cylindrical cross section ice detector will not detect ice at the lower pressure areas of the Whitcomb airfoil.

By using an airfoil-shaped ice detector probe assembly, similar pressure field conditions can be provided at both the wing and the ice detector probe assembly with the airfoil-shaped probe oriented at an angle of attack to provide a lower pressure region than the airfoil of the wing or placed in a region of local AOA amplification.

FIG. 4 is a representation of the ice detector shape in cross section, utilizing an NACA 0012 standard airfoil cross section shape probe assembly. This cross section shape probe assembly is used as a replacement for a cylindrical probe. A one-quarter inch diameter cylindrical probe is represented in FIG. **4** for comparison. The airfoil probe assembly **14** used was 2.08 inches long, and it will capture ice prior to the wing if it is located and oriented correctly. The conditions of operation for the representations shown in both FIGS. **4** and **5** are as follows and are arrived at using LEWICEv 1.6:

airspeed 150 KTAS;

angle of attack 12°;

altitude 10,000 feet;

MVD 20 microns;

LWC 0.25 g/m^3;

free stream static temperature 0.68° C.;

chord length 2.08 inches;

After only 10 seconds, ice formed on the ice detector probe assembly under these conditions. In these same conditions, there was no ice formation on the conventional ice detector. If the airfoil-shaped probe assembly is placed and oriented correctly, it can be shown that the critical temperature of the ice detector is now above the critical temperature for a Whitcomb airfoil with a local AOA of 10°.

Because the NACA 0012 airfoil has a different pressure distribution than the Whitcomb airfoil, it was necessary to modify the orientation of the NACA 0012 airfoil-shaped probe assembly from that of the wing. The critical static temperature for the Whitcomb airfoil at an angle of attack of 10° is +0.68° C. The NACA 0012 airfoil ice detector probe assembly was oriented at 12° angle of attack to obtain a critical static temperature warmer than +0.68° C.

The other aerodynamic issue is one of how the probe assembly is located. The local angle of attack change is often not a one-to-one relationship with the aircraft angle of attack. For this reason it is important to understand the placement of the ice detector strut and probe assembly on the aircraft.

In other words, the airfoil-shaped probe assembly is mounted at a location so that at the normal desired takeoff and landing angle of attack, the airfoil-shaped ice detector probe assembly will be in a pressure field that is similar to that of the airfoil on the aircraft on which the ice detector is used.

FIG. **5** is an enlarged section of the leading end of the airfoil-shaped ice detector probe, again plotted as Z/C versus X/C, using the same parameters as those recited for FIG. **4**. The ice accumulation is illustrated at **28**, and it accumulated in this area before ice formed on the Whitcomb airfoil wing at a slightly lower local AOA.

FIGS. **6**, **7** and **8** show a modified form of the present invention, wherein a strut and probe assembly **39** includes a cylindrical ice detector probe section indicated at **40** mounted onto a strut **41** fixed to a mounting flange **42** which is supported by the aircraft skin **44**. A housing **46** on the interior of the aircraft below the skin **44**, houses suitable excitation and sensing circuitry illustrated generally at **50**, which is of conventional design. The probe section **40** may be of the magnetostrictive type, and is vibrated in direction as indicated by the double arrow **52** by the excitation circuitry, and any change in the natural frequency of vibration caused by ice accretion on the surface of the probe will be detected by the sensing portion of the circuitry shown at **50**.

The probe section **40** is cylindrical, as can be seen in FIG. **8**, and in order to provide the ability to reliably detect ice prior to ice accretion on the aircraft skin **44** in the region that is to be protected from ice, the strut and probe assembly **39** includes a downstream or afterbody flat plate section **54** mounted onto an end surface **56** of the strut **41**, and extends upwardly closely adjacent and along the probe section **40** some desired amount. For example, the edge of the flat plate section **54** extends approximately 80% of the length of the probe section **40**. The length of the probe section **40** is measured from the surface **56** to the outer end of the rounded, hemispherical end portion **41**. The outer edge of the afterbody or flat plate section may be skewed or rotated with respect to surface **56** or parallel to surface **56** as shown, and can be rounded or tapered toward wall **56** in aft direction as well. (See FIGS. **9**, **10** and **11**)

The leading edge of the afterbody or flat plate section, indicated at **54A** is spaced from the trailing side of the probe

section **40**, as shown, by a distance equal to "d". The distance "d" can be in the range of 0.025 inches, for example, and is enough so that it will not affect the vibration of the probe section **40**, using the excitation and sensing circuitry.

In normal operation, the airflow around the conventionally shaped cylindrical cross section probe, from the direction indicated by arrow **55** in FIG. **6**, will separate at approximately 108° past the stagnation point. Vortices will be shed and the minimum pressure point will be at approximately 90° to the airflow direction. The magnitude of this minimum pressure will be close to the theoretical value of a pressure coefficient −3. If the flow remained attached all the way to the rear stagnation point, this would be the case, but because of the flow separation, this does not happen in practice. With the addition of the afterbody, the magnitude of the shed vortices is reduced and the flow remains attached longer. This, in turn, allows the minimum pressure at the maximum thickness of the cylinder to become more negative. The lower the pressure, the colder the air at that point.

FIGS. **9**, **10** and **11** show a further modified form of the invention, wherein the ice detector strut and probe assembly **63** includes a probe section **62** mounted onto a strut **64** supported on a plate **66** which is in turn supported on an aircraft skin **68** in a normal manner. The probe section **62** is of a magnetostrictive type, and energization and sensing circuitry shown at **70** is provided. The circuitry would normally be on the interior of the aircraft skin contained in a housing **65** and is shown only schematically.

In this form of the invention, an afterbody or flat plate section **72** is included in the strut assembly. This afterbody section **72** is a narrow, flat blade that is triangular in shape in top view and has an outer edge that tapers downwardly from the probe section **62** to the rear. The outer edge is rounded as well. The forward edge of afterbody **72** is spaced from the probe section **62** by a distance "d", which again, is in the desired range, for example, 0.025 inches. The side of the afterbody section **72** adjacent the probe sections may be approximately the same height as the afterbody section **54** shown on FIG. **8**, or somewhat shorter, and it will divide the flow so that as air flows around the cylindrical probe section **62** in the direction indicated by arrow **67**, it will create lower pressure on the lateral side areas indicated generally at **76**, as explained in connection with FIGS. **6**, **7** and **8**. As stated, with the addition of the afterbody, the magnitude of the shed vortices is reduced and the flow remains attached longer. This, in turn, allows the minimum pressure at the maximum thickness of the cylindrical probe section to become more negative. The lower the pressure, the colder the air at that point.

FIGS. **12**, **13** and **14** show a further modified form of the invention, wherein the ice detector strut and probe assembly **81** includes a strut **80** and a cylindrical probe section **82** mounted together onto a support flange or plate **83** that in turn is mounted onto an aircraft skin **84**. The probe section **82** is of a magnetostrictive type, and energization and sensing circuitry shown at **88** is provided. The circuitry would normally be on the interior of the aircraft skin contained in a housing **85**, and is shown only schematically.

In this form of the invention a forebody or flat plate section **86** is included in the strut and probe assembly **81**. The forebody section **86** is a narrow, flat blade that is triangular in shape in top view and has a leading edge that tapers upwardly from a leading end toward the probe section **82**. The trailing edge of forebody **86** is concave to conform to the cylindrical shape of the probe section, and is spaced from the probe section **82** by a distance "d", which again, is